

METHOD FOR INTERPOLATING AT LEAST TWO  
POSITION-DEPENDENT, PERIODIC ANALOG SIGNALS THAT  
ARE PHASE-SHIFTED WITH RESPECT TO ONE ANOTHER

Detailed Description

The present invention relates to a method for interpolating at least two position-dependent, periodic analog signals that are phase-shifted with respect to one another, according to the definition of the species in Claim 1.

Such a method is used to interpolate analog signals generated by scanning a measuring graduation, for position-measuring, i.e. especially for measurement of lengths and/or angles. In this connection, the analog signals are respectively converted into a digital data stream, with the aid of a sigma-delta modulator; for generating a (single) string of results, the at least two data streams are then first combined with correctional factors and subsequently with one another; and from the string of results, on the one hand, new correctional values are generated in the light of the quality criterion to be satisfied (by the values of the string of results), and on the other hand, the output signals of the interpolation are generated.

The at least two analog signals are particularly phase-shifted by  $90^\circ$  to one another, and are essentially sinusoidal, the latter also including analog signals generated from the sine function by phase-shifting, such as cosine signals.

Such a method is known from DE 199 38 802 A1. In this method, the string of results is supplied to a digital filter, which restores certain data of the input signals, and which subsequently increments or decrements a phase counter as a function of the output value of the filter. The phase value generated hereby is used on the one hand (up to the

fulfillment of the quality criterion) for determining new correctional values, and on the other hand for determining the output signal of the interpolation. For the satisfaction of the quality criterion, the string of results generates a  
5 signal sequence in a filter, at simultaneous decimation, which, after comparison to the quality criterion, controls the correctional values in such a way that the string of results approaches this quality criterion, and in addition, a string of addresses is formed from which, after low-pass filtering  
10 and association, the output signals are generated.

From DE 195 02 276 A1 an interpolation method is known for interpolating at least two sine-like analog signals, for measuring paths and/or angles, that are obtained by the  
15 scanning of a graduation carrier, are position-dependent, periodic and phase-shifted by  $90^\circ$  to one another, in which noise is superimposed on the analog signals in each case using sigma-delta modulation, in which, from the thus generated data strings, upon simultaneous first incomplete low-pass filtering  
20 of the noise components above the maximum input frequency of the analog signals, sequences of signals are generated, and in which, from the sequences of signals, a sequence of angular values is obtained to which is assigned, after a second low-pass filtering of the still-present noise component, above the  
25 maximum input frequency of the analog signals, a string of output values.

From DE 195 06 276 A1 a method is known for interpolating sensor signals, in which respectively one sine signal and one  
30 cosine signal of a sensor is supplied to a bridge circuit having several tapping points and a value comparison is carried out between a tapping pair, made up of two tapping points which lie diametrically opposite in the bridge circuit. If a value equality between the tapping pair is determined  
35 which corresponds to a zero crossing of the scanning value, a signal representing the setting of the corresponding tapping pair is emitted. In this context, the tapping pairs are

scanned one after another in one direction, are subjected, one after another, to the value comparison, and a count value is assigned to each scanning event. Appropriate to the result of the comparison, a phase counter is incremented or decremented.

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The present invention is based on the object of further improving an interpolation method of the type named at the outset.

10 This objective is achieved in accordance with the present invention by devising a method having the features of Claim 1.

According to that, the values of the string of results for generating the correctional values as well as the output  
15 signals are accumulated over a specifiable time interval, and the signal sequence generated by the accumulation is used directly as address sequence for generating the correctional values and the output signals.

20 Thus, according to the present invention, to form an address sequence, a phase counter is not simply incremented or decremented, but rather, by accumulation, a phase value having a fractional proportion is generated. Thereby is achieved a more exact phase correction, a lower gain of the loop used to  
25 satisfy the quality criterion, and consequently improved dynamics of the overall system. In the accumulation over a specified time interval (decimation of the data stream) the time interval is selected in such a way that, from the accumulated values of the string of results, the phase of the  
30 analog signals may specifically be determined.

The accumulation of the values of the string of results preferably takes place in a filter, and, to be sure, particularly in a filter in the form of an integrator.

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The address values of the address sequence formed by the accumulation represent in each case the phase information of

the input-side analog signals, and are linearly dependent on the phase of at least one periodic analog signal, when the quality criterion is satisfied. That means, that if the generation of the output signals has advanced so far that the string of results or the address sequence generated therefrom approach a predefined quality criterion, there is then a linear association between the address values and the phase of the input-side analog signals.

Finally, from the address sequence, the output signals of the interpolation are able to be generated by low-pass filtering and subsequent assignment of the address values.

According to the present invention, the address values of the address sequence represent a phase value having a fractional component, for the generation of the correctional value the high-value part of the address sequence being used, which corresponds to an incremental component of the address sequence, and, for the generation of the output signals of the interpolation, the high-value and the low-value part of the address sequence being used. The latter corresponds to the fractional part of the address sequence.

The higher-value part of the address sequence is defined in such a way that the address depth of the correctional values assures the desired interpolation. If, for example, the period of a sine type of input-side signal is to be subdivided 32-fold for the desired interpolation, the higher-valued part of the address sequence must have a width of 5 bits. The remaining, low-valued part of the address sequence determines the fractional component of a phase increment.

All in all, the determination of the output signals of the interpolation takes place recursively, using a closed loop, in that, in the light of the quality criterion, new correctional values are generated and combined with the digital data

streams generated from the input-side analog signals, as long as the quality criterion is satisfied.

5 The possible correctional values, in which particularly values of trigonometric functions (sine functions and/or cosine functions) may be involved, may be stored as predetermined values in an assignment unit. From the values stored in the assignment unit, the correctional values to be combined respectively with the individual data of the digital data streams are selected in the light of the quality criterion, as a function of the current address values of the address sequence. In this context, the quality criterion may optionally be applied directly to the values of the string of results, in that, a corresponding combining unit is  
10 preconnected to the filter (integrator) that is used for generating the address sequence, or this combining unit is combined with the filter (integrator) to form one unit.  
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For the generation of the string of results, the individual data of the digital data streams generated from the input-side analog signals are in each case combined multiplicatively with a correctional factor, and subsequently the data of different data streams are combined with one another by addition or subtraction.  
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25 The sigma-delta modulator is preferably designed in such a way that the individual data of the digital data streams, generated thereby, in each case have a word width of only one bit.

30 In the case of an exact phase position and a sinusoidal pattern of the input-side analog signals, the values  $d$  of the string of results are formed according to the formula  $d = s_1 \cdot k_1 \pm s_2 \cdot k_2$ , where  $s_1$ ,  $s_2$  are data of the digital data streams generated using the sigma-delta modulation, and  $k_1$ ,  $k_2$  are assigned correctional factors. In this context, the address sequence generated by accumulation of the values  $d$  of  
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the string of results influences the correctional values in such a way that a linear association with the angular information of the input-side analog signals is produced.

5 If, in the data of the data streams generated by the sigma-delta modulation, data having a word width of one bit are involved, then the multiplication  $s_1 \cdot k_1$  and  $s_2 \cdot k_2$  yields the values  $k_1$  at  $s_1 = 1$ , and  $-k_1$  at  $s_1 = 0$ , and  $k_2$  at  $s_2 = 1$  and  $-k_2$  at  $s_2 = 0$ . At sufficient word width of the correctional  
10 values  $k_1$ ,  $k_2$ , the complement may occur in a simplified manner by the complement on one.

Since, in the case of a word width of one bit, for the data of the digital data streams as the result of the above-explained  
15 combination for generating the values  $d$  of the string of results, exactly four cases may be distinguished, the said combination (arithmetic operation)  $s_1 \cdot k_1 \pm s_2 \cdot k_2$  may be combined. The four cases may be represented arithmetically as the sum  $k_1 + k_2$  of the correctional values, the difference  
20  $k_1 - k_2$  of the correctional values, as well as their negatives. If these differences and sums are stored as correctional values, the expenditure for the arithmetic operations is reduced even more.

25 A digital interpolation device for carrying out the method according to the present invention is characterized by the features of Claim 20.

Other features and advantages of the present invention are  
30 clarified in the following description of exemplary embodiments of the present invention, in the light of the figures. The figures show:

Figure 1 a schematic representation of an interpolation  
35 device and the appertaining interpolation method for application in the case of position encoders to the

measuring of paths and/or angles, by way of a block diagram.

5 The starting point of the block diagram shown in Figure 1 is at least two analog signals a1 and a2 that are similar to sines, phase-shifted by  $90^\circ$  with respect to one another, periodic, position-dependent, and obtained by scanning in a position encoder 1 of a measuring system, which are to be used for measuring paths and/or angles. They are in each case  
10 converted using sigma-delta modulation in a sigma-delta modulator 3 into digital data streams s1, s2 (word sequences) of high frequency and low word width, in which amplitude information is contained in the distribution over time of the data. The two data streams s1, s2 having m bit-wide data are  
15 accordingly created from analog signals a1 and a2 in each case by superimposition of a noise signal. This noise signal results from the quantization noise of the sigma-delta modulation.

20 The data of the digital data streams s1, s2 are multiplied in a multiplication unit 6 of an arithmetic unit 5 respectively by correctional values k1, k2 from an assignment unit 4, in which a specifiable number of possible correctional values is stored. From the two new strings m1, m2, formed by  
25 multiplication of the data by the correctional values k1, k2, a single string of results d is formed by addition or subtraction of the words of those strings m1, m2 in an addition/subtraction unit 7 of arithmetic unit 5.

30 After the combination with a quality criterion k3, the values of string of results d are supplied from assignment unit 4 in combination unit 8 to a filter in the form of an integrating unit 9, in which it is accumulated for the formation of an address sequence a over a specifiable time period. A part  
35 (namely, the higher-value part) of the value accumulated in integration unit 9 is in turn combined with a value from assignment unit 4, and the combination result is used directly

for addressing for the selection of new correctional values  $k_1$ ,  $k_2$  from assignment unit 4 for multiplication by data of the sigma-delta modulation. Alternatively, combination unit 8 may also be positioned behind filter 9, the addressing of the correctional values in assignment unit 4 then taking place of a part of the output value of post-connected unit 8.

In case the quality criterion is not equal to zero, that is, the input-side analog signals are not sinusoidal or cosinusoidal, quality criterion  $k_3$  is ascertained in an appropriate manner, as was described above in the light of correctional values  $k_1$ ,  $k_2$ .

In the adjusted state, the addresses of the address sequence oscillate between discrete values which represent the best approach to the exact phase setpoint value of the input signals. Output signal  $w$  of the interpolation is formed by closing additional filtering and assignment in an evaluation circuit 10, which includes a digital low-pass filter 11 and an assignment unit 12.

The output of output signal  $w$  takes place as a function of the assignment unit in the form of two square-wave signals that are phase-shifted with respect to each other by  $90^\circ$ , or it takes place in any other desired form (binary, Gray code, ...).

Similar to the case of network interpolators, the phase information is obtained during the conversion, and it consists of a linear association between the change of the angular value of input-side analog signal  $a_1$  or  $a_2$  and the change of output value  $w$ .

A digital interpolation device is used for the implementation of the above-described method.



Input signals of the interpolation device form two analog signals  $a_1$  and  $a_2$ , that are similar to sines and are phase-shifted with respect to each other by  $90^\circ$ , for instance, coming from incremental position encoders that are known per se. In the interpolation device according to the present invention, from the two analog signals  $a_1$  and  $a_2$ , the output value  $w$  is obtained having the resolution resulting from the demanded degree of interpolation.

First, the two analog signals  $a_1$  and  $a_2$  are each supplied to a sigma-delta modulator 3. The output signals of sigma-delta modulators 3, two digital data streams  $s_1$ ,  $s_2$  having data of low width (e.g. words of 1-bit width) are multiplied in multiplication unit 6 of arithmetic unit 5 by one correctional value  $k_1$ ,  $k_2$ , respectively, of assignment unit 4, and, after addition or subtraction of the sequences to/from each other in addition/subtraction unit 7 of arithmetic unit 5, the values of string of results  $d$  are supplied to integrator 9, whose output signal is an address sequence  $a$  composed of address values.

One part of address sequence  $a$  is additionally combined with a value from assignment unit 4. The result of the combination determines the selection of correctional values from assignment unit 4 in such a way that a quality criterion  $k_3$  is achieved.

The address values of address sequence  $a$  represent the phase information sought, acted upon by low residual noise.

Subsequent filtering of the address values and the assignment forms interpolated output  $w$ .

The possible correctional values  $k_1$ ,  $k_2$ , which are selected as a function of the current address value, may be stored in assignment unit 4, for example, in the form of a table. If, for instance, in the case of possible correctional values  $k_1$ ,  $k_2$ , values each of a trigonometric function are involved, this

means that, for a certain number of points (e.g. for 16 points), from the value range of the corresponding trigonometric function (e.g. a sine or a cosine function), the respective appertaining functional value is stored from the value range of the trigonometric function as a possible correctional value in the table mentioned above.

Here is a concrete example of this: If the possible values of the one correctional value  $k_1$  are determined to be functional values of a cosine function, then, accordingly, for 16 points out of the definition range ( $0^\circ - 360^\circ$ ) of the cosine function of the respective appertaining functional value (e.g. the functional value  $\cos 0^\circ = 1$  for the value  $0^\circ$  of the definition range, the functional value  $\cos 22.5^\circ$  for the value  $22.5^\circ$  of the definition range, the functional value  $\cos 45^\circ$  for the value  $45^\circ$  of the definition range, etc.) is stored as the possible value of correctional value  $k_1$  in the table provided for it. From these 16 functional values stored in the table, the respective correctional value  $k_1$  is then selected. The other correctional value  $k_2$  may be represented in corresponding fashion, such as by functional values of a sine function.

The width of the correctional values should be selected in such a way that at least the number of different functional values can be represented, i.e. for 16 different functional values from which a correctional value is selected, its width is at least 4 bits. For 32 different functional values, the width of the correctional value would be at least 5 bits, etc. The width of correctional values  $k_1$ ,  $k_2$ , in turn, determines (especially if the word width of the data of the two digital data streams  $s_1$ ,  $s_2$ , that are to be combined with them, amounts to only 1 bit) the width of the values of string of results  $d$ , and thus also the address values of address sequence  $a$ .

Arithmetic unit 5 may, for example, be implemented as follows:

- Arithmetic unit 5 includes two multiplication devices 6, in such a way that, by multiplication, two strings  $m1 = s1*k1$  and  $m2 = s2*k2$  are formed from digital data streams  $s1$ ,  $s2$  and correctional values  $k1$ ,  $k2$  of assignment unit 4, the multiplication by correctional values  $k1$ ,  $k2$  being made in each case for the individual data of data streams  $s1$ ,  $s2$ . Subsequently, in addition/subtraction unit 7 the difference  $m1 - m2$  of the two product strings  $m1$ ,  $m2$  is continuously formed.

- At a bit width  $m = 1$  of the individual data of digital data streams  $s1$ ,  $s2$ , the multiplication in multiplication device 6 consists in leaving the value of assignment unit 4 uninfluenced if  $s1 = '1'$  or  $s2 = '1'$ , and in negating if  $s1 = '0'$  or  $s2 = '0'$ .

- At bit width  $m = 1$  of the individual data of digital data streams  $s1$ ,  $s2$ , there are yielded at the two outputs of sigma-delta modulators 3, taken as words, only four different states which, including the addition and subtraction, determine the sums and differences of the values of assignment unit 4 and their negation. When these values are stored in assignment unit 4, this may simplify the addition and subtraction unit and assignment unit 4.

Integrator 9 is an accumulator in the simplest case. Combination unit 8 is not needed when there is an exactly sinusoidal pattern to input-side analog signals  $a1$ ,  $a2$  and a phase position of the analog signals of  $90^\circ$  to each other, since the quality criterion becomes  $k3 = 0$  (phase offset). In the case of other signal curves, the values of string  $d$  should be combined with quality criterion  $k3$  from assignment unit 4 (addition/subtraction). Integrator 9 directly addresses assignment unit 4 (e.g. ROM) and after final filtering 11 and assignment 12 represents the output signal of interpolating device 2.

In the following, the effect of interpolating device 2 will be described in greater detail. Interpolating device 2 evaluates the two sine-like analog signals a1 and a2 (sine or cosine signal) supplied by position encoder 1 and phase-shifted by 90° with respect to each other, in such a way that output signal w of interpolating device 2 represents the path change detected by position encoder 1. Analog signals a1 and a2 supplied by position encoder 1 are changed in the appertaining sigma-delta modulators 3 into two m-bit-wide word strings s1, s2 (digital data streams) of high frequency and low word width of the data. The amplitude information of analog signals a1 and a2 are included in the distribution over time of the data of the two digital data streams s1, s2, at the output of these sigma-delta modulators. Multiplication unit 6, that is subsequent to each of the two data streams s1, s2, forms the new strings m1 and m2 from modulator strings s1, s2 and correctional values k1 and k2 from assignment unit 4. From these strings m1, m2 string of results d is generated in addition and subtraction unit 7, and combined with a quality criterion obtained from assignment unit 4 is supplied to integrator 9.

If there is an exactly sinusoidal curve of input signals a1 and a2, the integrator restores the information  $\beta = \alpha$  according to  $\sin(\alpha) \cdot \cos(\beta) - \cos(\alpha) \cdot \sin(\beta) = \sin(\alpha - \beta)$ , where  $\sin(\alpha)$  and  $\cos(\alpha)$  represent input-side analog signals a1, a2, and  $\cos(\alpha)$  or  $\sin(\beta)$  represent the correctional values k1 and k2 of assignment unit 4, and  $\sin(\alpha - \beta)$  is proportional to the phase increment per scanning.

Other conversion functions may be selected for other kinds of input signals, for example, for correcting errors of the position encoder. In the case of sinusoidal input signals a1, a2,  $\sin(\alpha - \beta)$  is minimized so as to achieve the quality criterion. In other words, the quality criterion is satisfied for  $\alpha = \beta$ . If  $\beta$  is the counter value (address value of

assignment unit 4), then, if  $\sin(\alpha - \beta) = 0$ ,  $\beta$  becomes  $= \alpha$  and  $\beta$  thus corresponds to the phase position of the input signals.

To summarize, the object of creating a digital interpolation  
5 for increasing the resolution of preferably incremental  
measurement of lengths and/or angles is realized in that, for  
one, the advantages of the sigma-delta modulation are utilized  
in converting analog input signals into digital data streams.  
The method of the sigma-delta A/D conversion was chosen  
10 because the proportion of analog circuit components is reduced  
and a high resolution is achievable in the digital part. By  
utilizing the low-bit output signals of the sigma-delta  
modulators as input information for an arithmetic unit,  
arithmetical operations such as multiplication are greatly  
15 simplified. The formation of only one criterion to be  
evaluated further simplifies the digital evaluation circuit  
(digital filter) and thereby also the circuit integration.

The properties of the method make it possible to integrate the  
20 non-linear A/D conversion largely into the digital part of the  
circuit, so that the interpolating device can be developed as  
an integrated circuit. The errors created by other methods,  
on account of non-ideally analogous component parts, are  
largely avoided.

25 Going into details, an interpolating method and an  
interpolating device are proposed, for signal subdivision  
(interpolation) of two analog signals (optionally voltage or  
current) that are sinusoidal and phase-shifted by  $90^\circ$  with  
30 respect to each other, especially from incremental position  
encoders for measurement of lengths and/or angles, in which  
the analog signals are in each case converted using sigma-  
delta modulation into a data stream of low bit width, in which  
each item of data from the data stream thus created is  
35 multiplied by values from an assignment unit in the case of  
which the product values of one sequence is added to or  
subtracted from the product values of the other sequence, and

the string of results thus generated is accumulated, and a part of the accumulation value controls an address unit in such a way that this address unit, on the one hand, addresses the assignment unit and, on the other hand, the output signals  
5 are formed via an assignment unit.

An important advantage of the method described above and the appertaining interpolating device is that method steps using correction and having "sigma-delta A/D conversion" are  
10 combined, and, in this context, one may do without a costly network, and also, the conversion of the input data into position values is carried out in one step, using the digital conversion with the aid of the sigma-delta modulation. By combination of the principle of correction to the simple  
15 sigma-delta A/D conversion, the analog part of the interpolating device is reduced to a minimum and its digital part is simplified. It is possible to construct the entire interpolating device as an integrated circuit, using easily  
20 available technologies.